Analysis of Different Responses of Ion and Electron in Six-Field Landau-Fluid ELM Simulations

BOUT++
Boundary Plasma Turbulence Code

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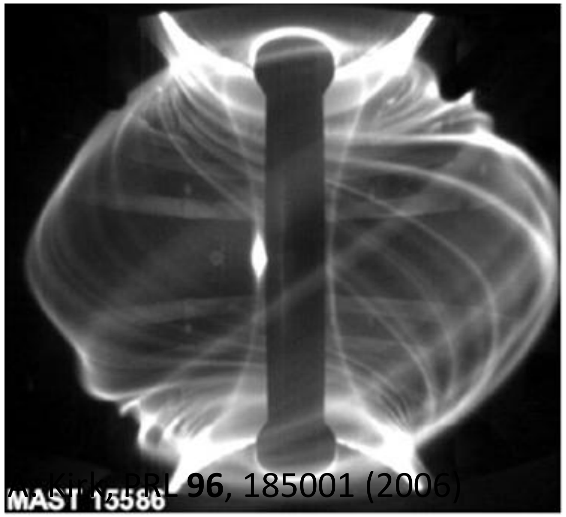
Outline

1. Introduction
2. Physics Model
3. Simulation Result
   1) Effect of different parallel heat flux closures
   2) L_n/L_t scan
   3) Different response of ion and electron
   4) Effect of thermal force
4. Summary

Background

- H-mode
  - Better power confinement for plasmas
  - Edge transport barrier and pedestal region
- ELMs
  - Periodic MHD events at H-mode pedestal;
  - Damage to PFC;
  - Affect confinement;
- Peeling-ballooning model
  - Driven by combination of high pressure gradient and current
  - Different linear instabilities, different types of ELMs.



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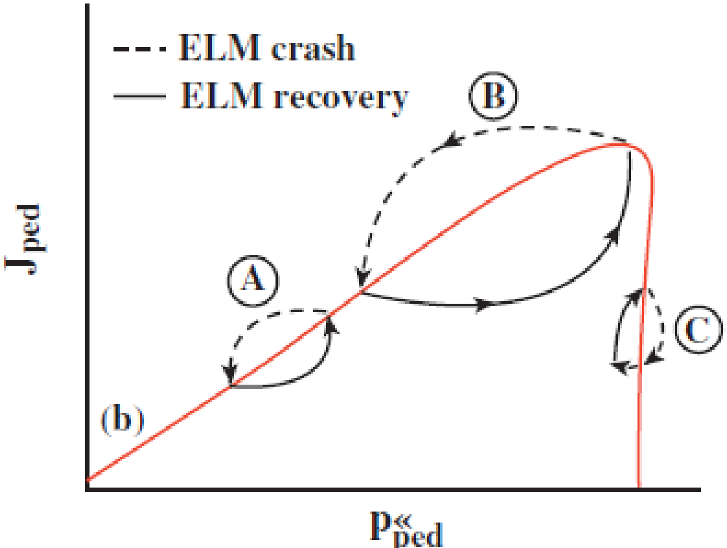

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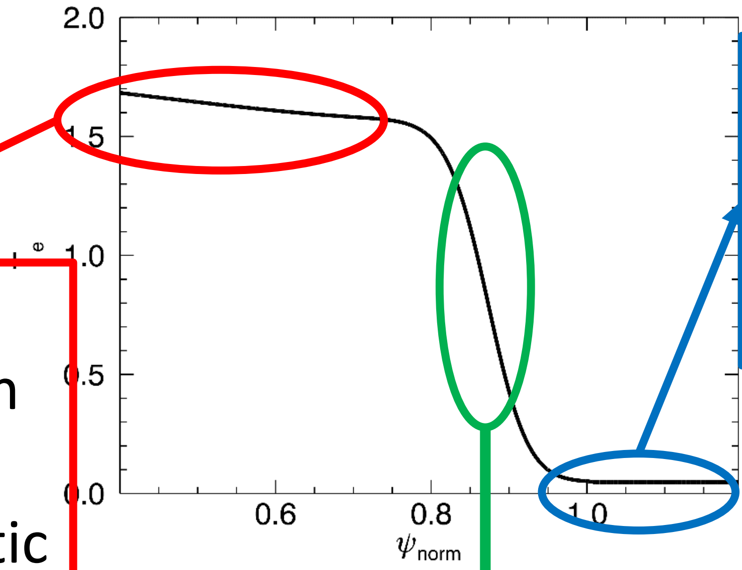
Landau fluid model can fill the gap between hot and cold boundary plasma



Core region

- Temperature: high
- Collision: weak
- Model: gyro-kinetic

Boundary region

- Temperature: low
- Collision: strong
- Model: two fluid

Landau closure

Two fluid model

Landau fluid model

✓ Two fluid model for ideal peeling-ballooning mode
✓ Using non-local transport closure to simulate kinetic effect on hot, collisionless region

6-field includes the effect of thermal conductivity and temperature profile

Model	Variables	Physics
3-field	$\varpi, A_{\parallel}, P$	Peeling-ballooning model
6-field	$\varpi, A_{\parallel}, n_i, V_{\parallel i}, T_i, T_e$	+Thermal conductivity

- 3-field:
  - Only peeling-ballooning model
- 6-field:
  - Thermal conductivity
    - Landau closure: collisionless wave-particle resonances
    - Flux limited heat flux: collisional transport and flux streaming
  - Effect of temperature profile → $\eta_i = L_n/L_T$ scan

6-field Landau fluid model with parallel heat flux

Vorticity:

$$\frac{\partial}{\partial t}\varpi = -\left(\frac{1}{B_0}b\times\nabla_\perp\phi + V_{\parallel i}b\right)\cdot\nabla\varpi + B^2\nabla_\parallel\left(\frac{J_\parallel}{B}\right) + 2b\times\kappa\cdot\nabla P$$
$$-\frac{1}{2\Omega_i}\left[\frac{1}{B}b\times\nabla P_i\cdot\nabla\left(\nabla_\perp^2\phi\right) - Z_i eBb\times\nabla n_i\cdot\nabla\left(\frac{\nabla_\perp^2\phi}{B}\right)^2\right]$$
$$+\frac{1}{2\Omega_i}\left[\frac{1}{B}b\times\nabla\phi\cdot\nabla\left(\nabla_\perp^2 P_i\right) - \nabla_\perp^2\left(\frac{1}{B}b\times\nabla\phi\cdot\nabla P_i\right)\right] + \mu_{\parallel i}\nabla_{\parallel 0}^2\varpi$$

Ion density:

$$\frac{\partial}{\partial t}n_i = -\left(\frac{1}{B_0}b\times\nabla_\perp\phi + V_{\parallel i}b\right)\cdot\nabla n_i - \frac{2n_i}{B}b\times\kappa\cdot\nabla\phi - \frac{2}{Z_i eB}b\times\kappa\cdot\nabla P - n_i B\nabla_\parallel\left(\frac{V_{\parallel i}}{B}\right)$$

Ion parallel velocity:

$$\frac{\partial}{\partial t}V_{\parallel i} = -\left(\frac{1}{B_0}b\times\nabla_\perp\phi\right)\cdot\nabla n_i - \frac{1}{m_i n_i}b\cdot\nabla P$$

Ohm's law:

$$\frac{\partial}{\partial t}A_\parallel = -\nabla_\parallel\phi + \frac{\eta}{\mu_0}\nabla_\perp^2 A_\parallel + \frac{1}{en_e}\nabla_\parallel P_e + \boxed{\frac{\alpha_e k_B}{e}\nabla_\parallel T_e} - \frac{\eta_H}{\mu_0}\nabla_\perp^4 A_\parallel$$

Thermal force

Ion temperature:

$$\frac{\partial}{\partial t}T_i = -\frac{2}{3}T_i\left[\left(\frac{2}{B}b\times\kappa\right)\cdot\left(\nabla\phi + \frac{1}{Z_i en_i}\nabla P_i + \frac{5k_B}{2Z_i e}\nabla T_i\right) + B\nabla_\parallel\left(\frac{V_{\parallel i}}{B}\right)\right]$$
$$-\left(\frac{1}{B_0}b\times\nabla_\perp\phi + V_{\parallel i}b\right)\cdot\nabla T_i - \boxed{\frac{2}{3n_i k_B}\nabla_\parallel q_i} + \frac{2m_e}{m_i}\frac{Z_i}{\tau_e}\left(T_e - T_i\right)$$

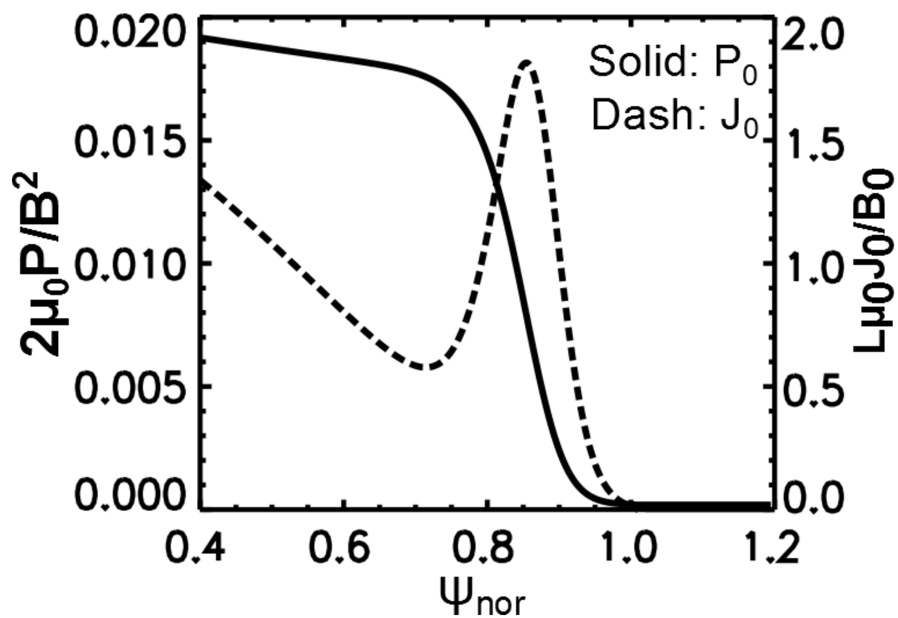
Parallel heat flux

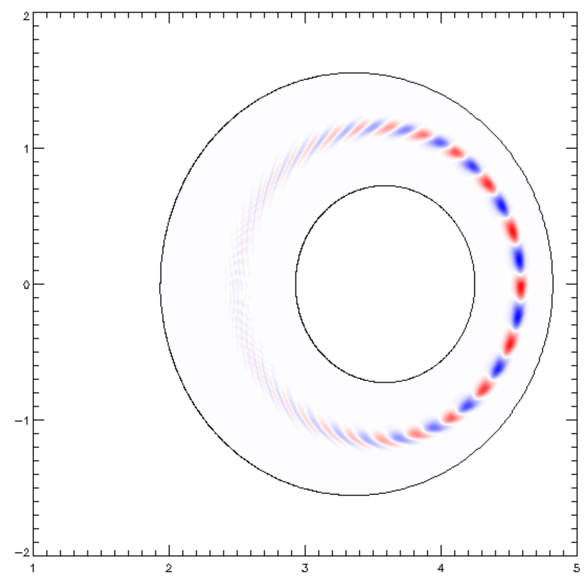
Electron temperature:

$$\frac{\partial}{\partial t}T_e = -\frac{2}{3}T_e\left[\left(\frac{2}{B}b\times\kappa\right)\cdot\left(\nabla\phi + \frac{1}{en_e}\nabla P_e + \frac{5k_B}{2e}\nabla T_e\right) + B\nabla_\parallel\left(\frac{V_{\parallel e}}{B}\right)\right]$$
$$-\left(\frac{1}{B_0}b\times\nabla_\perp\phi + V_{\parallel e}b\right)\cdot\nabla T_e - \boxed{\frac{2}{3n_i k_B}\nabla_\parallel q_e} - \frac{2m_e}{m_i}\frac{Z_i}{\tau_e}\left(T_e - T_i\right) + \frac{2}{3n_e k_B}\eta_\parallel J_\parallel^2$$

Different balance pressure profile

- Simulations are based on the shifted circular cross-section toroidal equilibria (cbm18_den6) generated by the TOQ code*.





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Classical thermal conductivities and Landau damping closure

Landau damping closure

$$q_{\parallel i} = -n_0 \sqrt{\frac{8}{\pi}} v_{T_{\parallel i}} \frac{i k_\parallel k_B T_i}{|k_\parallel|}$$

$$q_{\parallel e} = -n_0 \sqrt{\frac{8}{\pi}} v_{T_{\parallel e}} \frac{i k_\parallel k_B T_e}{|k_\parallel|}$$

✓ **Non-local thermal transport**

classical thermal conductivities

$$q_{\parallel i} = -\kappa_{\parallel i} \nabla_\parallel k_B T_i$$
$$q_{\parallel e} = -\kappa_{\parallel e} \nabla_\parallel k_B T_e$$

Where

$$\kappa_{\parallel i} = \left({\kappa_{\parallel i}^{SH}}^{-1} + {\kappa_{\parallel i}^{FS}}^{-1} \right)^{-1}$$
$$\kappa_{\parallel e} = \left({\kappa_{\parallel e}^{SH}}^{-1} + {\kappa_{\parallel e}^{FS}}^{-1} \right)^{-1}$$

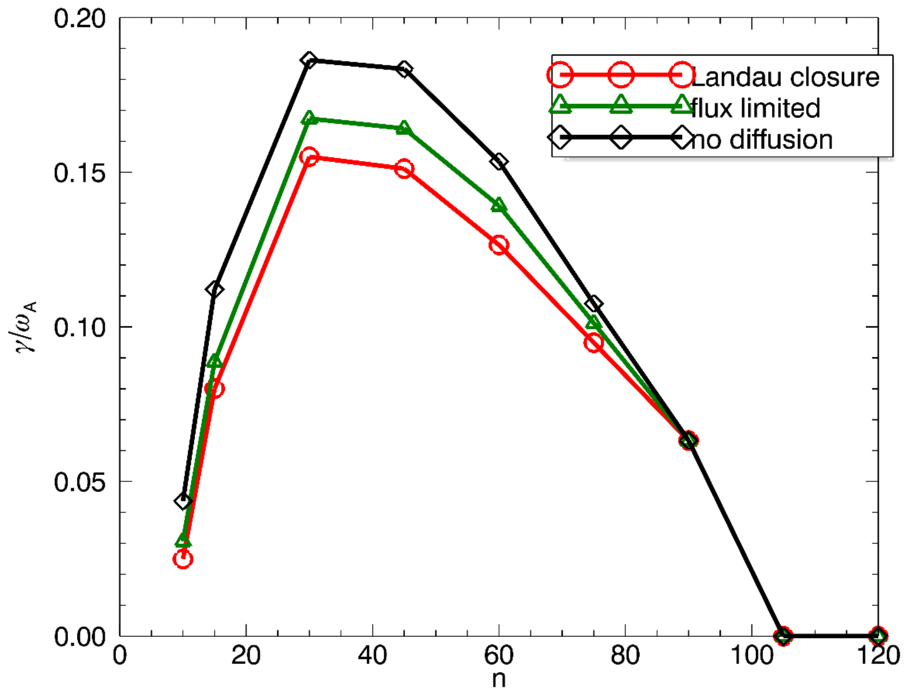
$$\boxed{\begin{aligned} \kappa_{\parallel i} &= 3.9 n_i v_{th,i}^2 / \nu_i \\ \kappa_{\parallel e} &= 3.2 n_e v_{th,e}^2 / \nu_e \end{aligned}} \rightarrow \text{Spitzer-Harm}$$

$$\boxed{\kappa_{\parallel j}^{FS} = n_j v_{th,j} q R_0} \rightarrow \text{Flux streaming}$$

✓ **Classical heat flux**

Landau closure has more damping effect on linear growth rate, but not very strong

- Both Landau closure and flux limited thermal conductivity has stabilizing effect on peeling-ballooning modes;
- Landau closure has stronger stabilizing effect;
- Thermal conductivity doesn't change the unstable island of modes.



Why the stabilizing effect from local/nonlocal parallel thermal conductive is not that strong?

Landau Damping and flux limited conductivity should have no effect on rational surface

- For ideal ballooning mode, dispersion relation is

$$\omega\left(\omega - \boxed{i\chi_{\parallel}k_{\parallel}^{2}}\right) + \gamma_I^2 = 0$$

Parallel conductivity effect

- We get growth rate

$$\gamma = \frac{1}{2}\left(-\chi_{\parallel}k_{\parallel}^{2} + \sqrt{\chi_{\parallel}^{2}k_{\parallel}^{4} + 4\gamma_i^2}\right)$$

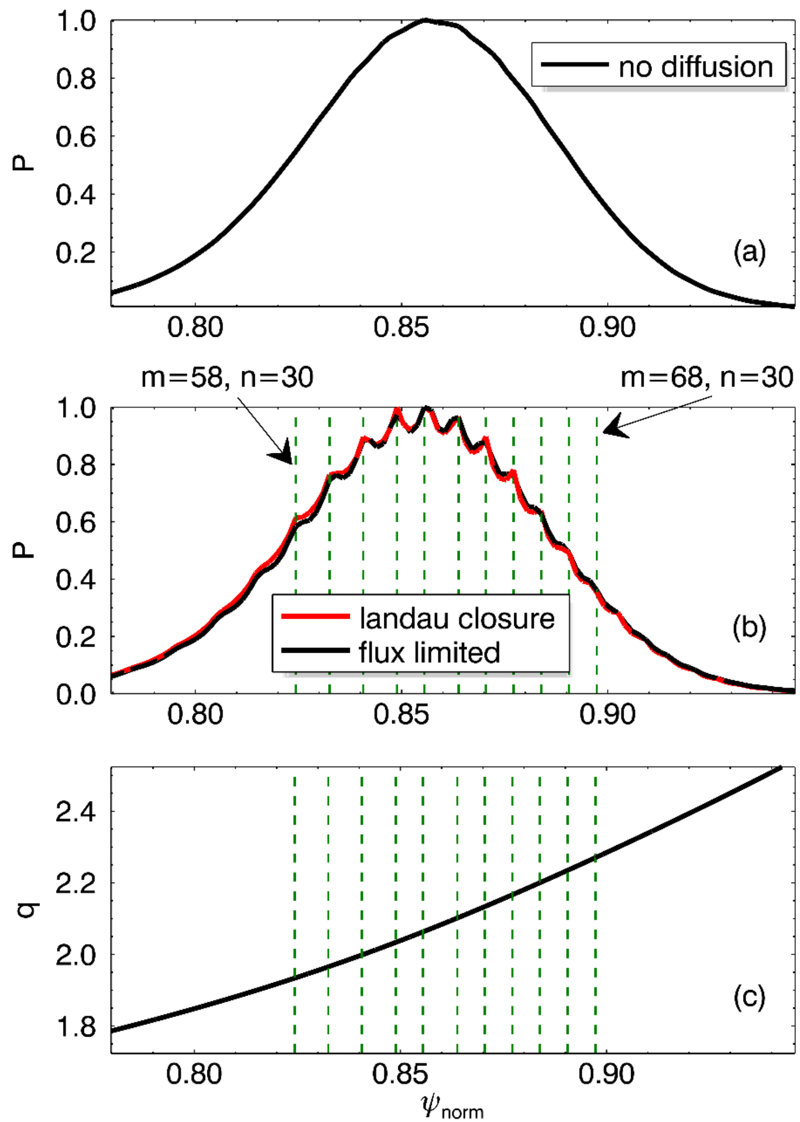
- Parallel conductivity has a stabilizing effect on peeling ballooning mode
- **Parallel conductivity should have no effect on rational surface which $\boldsymbol{k_{\parallel} = 0}$** → **Radial structure**

Our simulations show consistent radial structure with theoretic expectation!

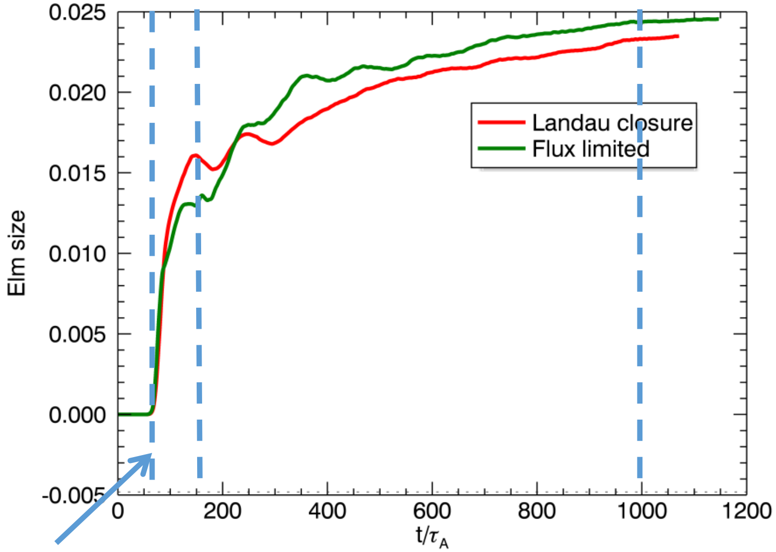
- Radial mode structure
  - Without parallel diffusion: smooth;
  - With Landau damping for flux limited thermal conductivity: peaked at rational surface.

	Rational surface	Irrational surface
Instability	Strong	Weak
Parallel damping	Weak	Strong

- The mismatch between instability and parallel diffusion reduces the damping effect on peeling ballooning modes.

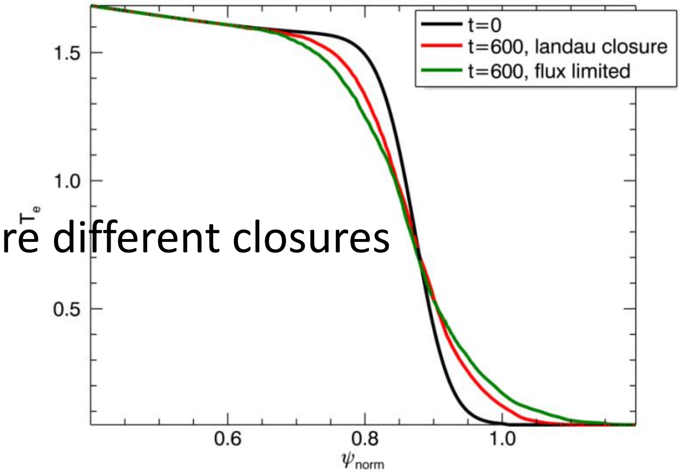


Landau damping leads to smaller ELM size in nonlinear simulations than flux limited expression

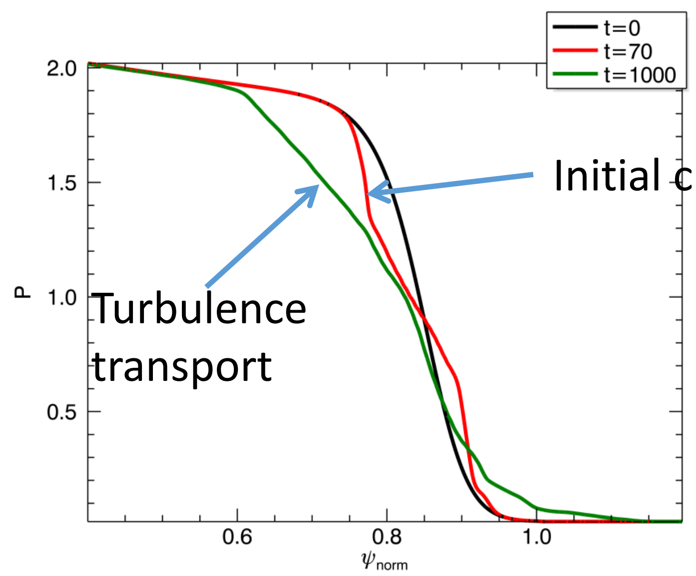


Elm crash

Turbulence transport



Compare different closures

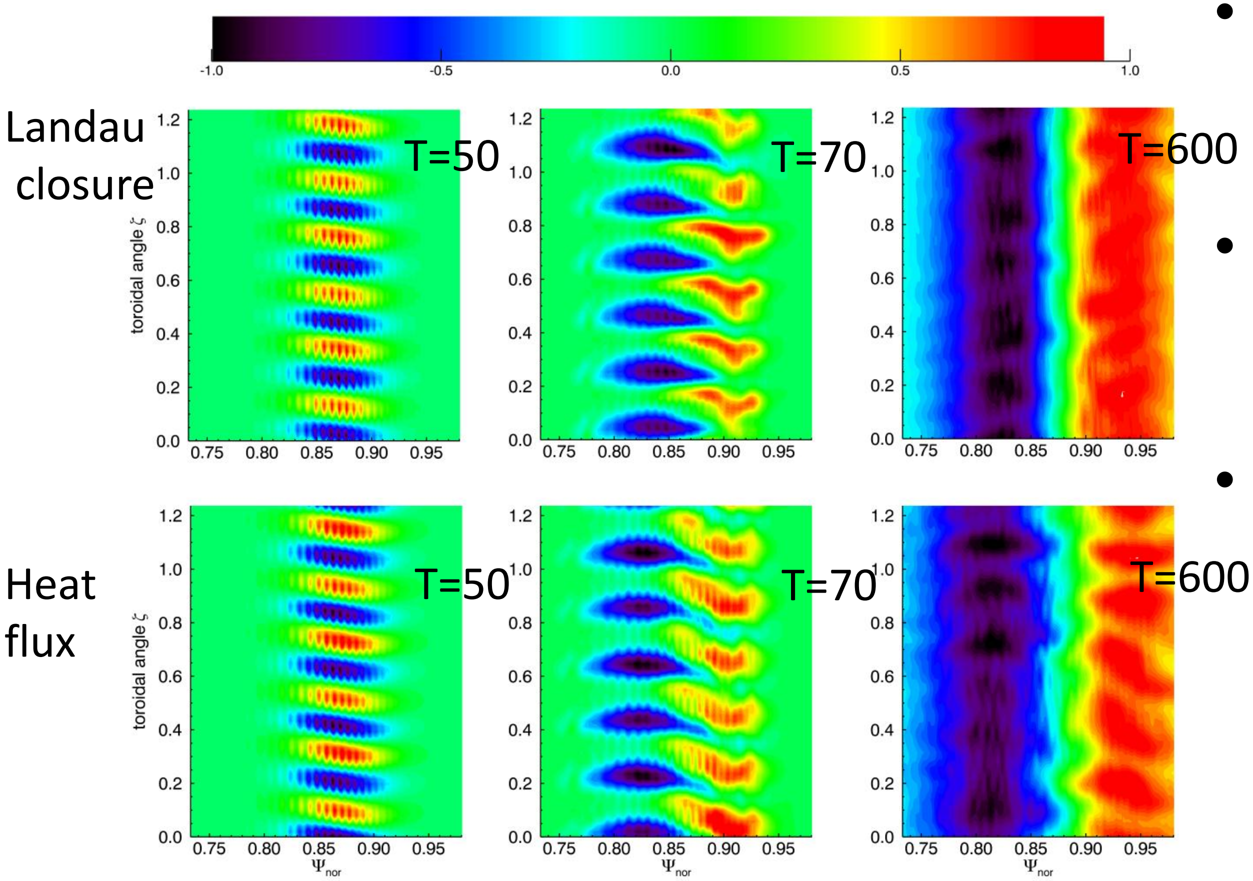


Initial crash

Turbulence transport

- Nonlinear result is similar as linear result;
- Landau damping closure has more damping effect on the turbulence transport phase of elm crash;
- Elm size with Landau closure is smaller than Elm size with flux limited heat flux;

Effect on rational surface during linear phase

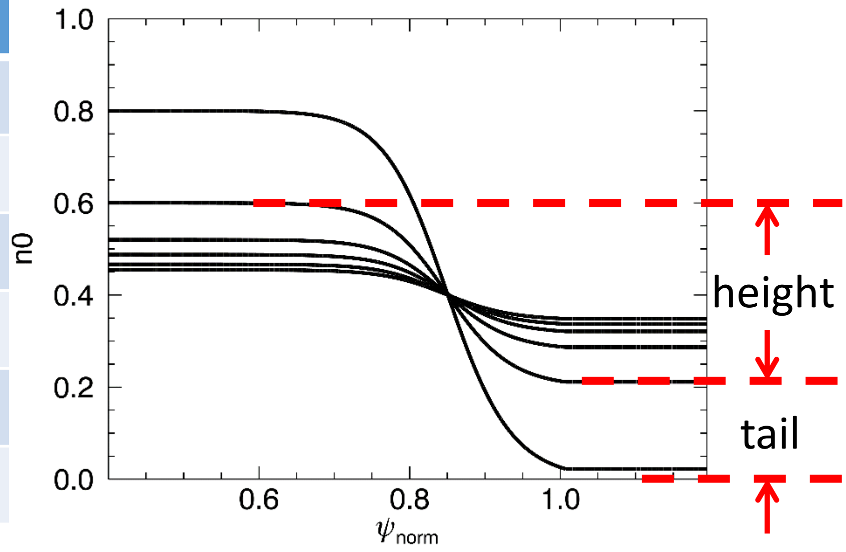


- Electron temperature contour of nonlinear run
- Parallel heat flux has no effect on rational surface
- Trace of rational surface disappear in the turbulence state

Different L_n/L_t

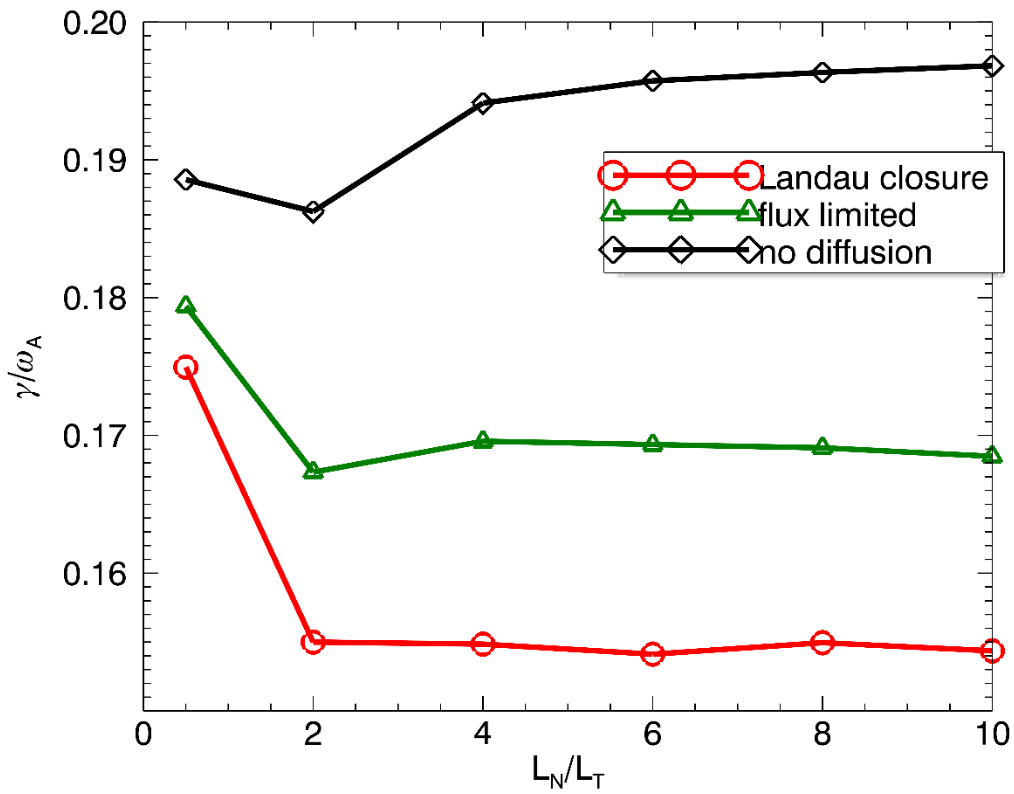
- Keep the same pressure profile, change density and temperature;
- L_n/L_t scan:

L_n/L_t	Height	tail
0.5	0.800	0.000
2	0.400	0.200
4	0.240	0.280
6	0.171	0.316
8	0.133	0.333
10	0.109	0.345



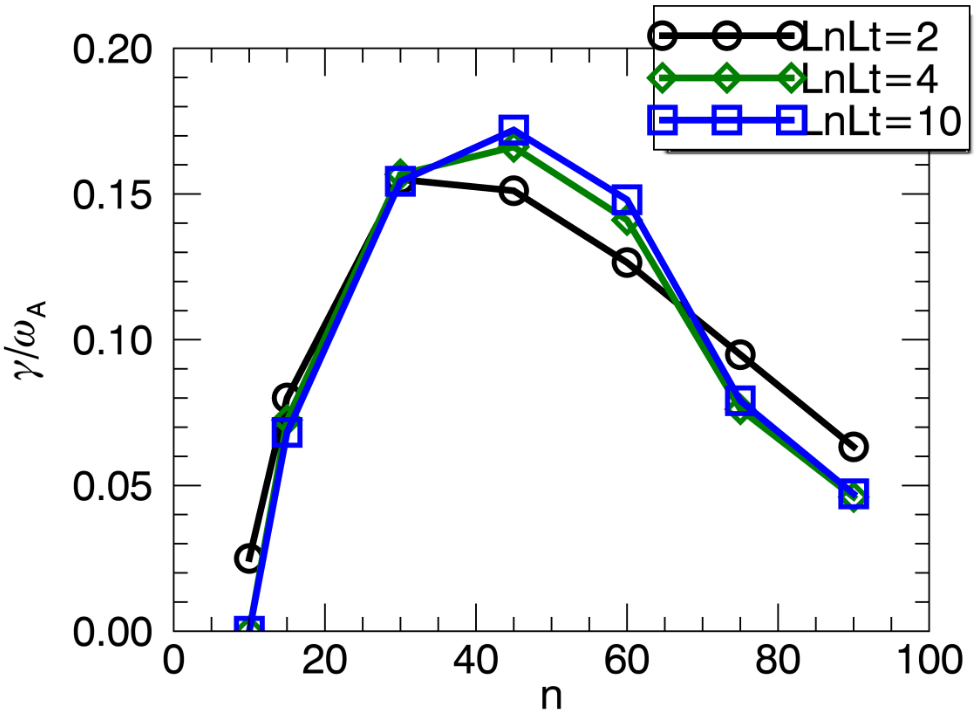
Damping effect is strong when L_n/L_T is large

- Keep pressure profile and local density and temperature profile fixed, change L_n/L_T
- L_n/L_T has small effect on peeling ballooning mode
- Parallel conductivity has small effect when L_n/L_T is small



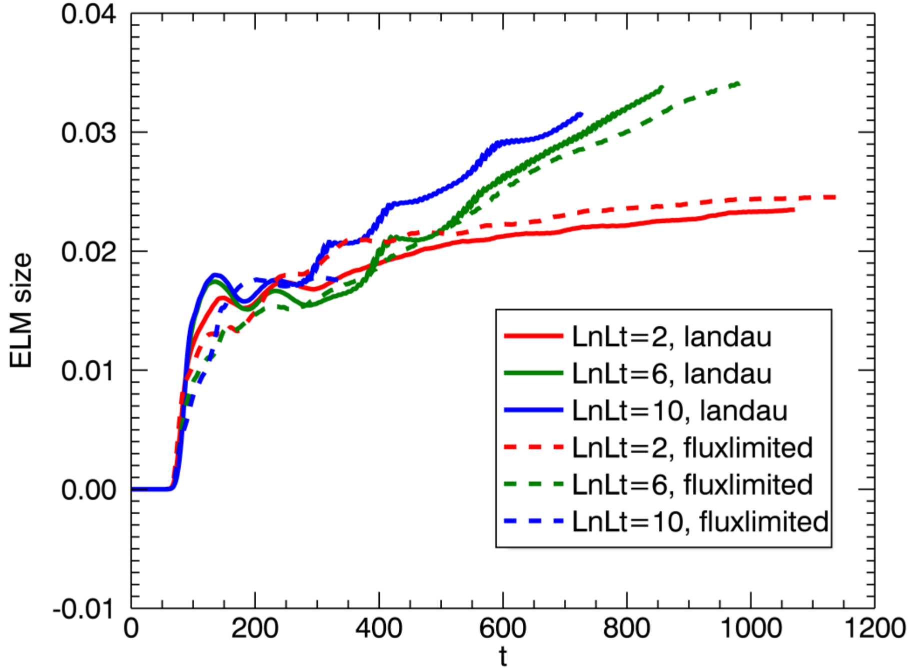
L_n/L_T has little effect on growth rate spectrum

- L_n/L_T has small effect on the growth rate and spectrum;
- Small effect from diamagnetic term because of different density gradient profile.



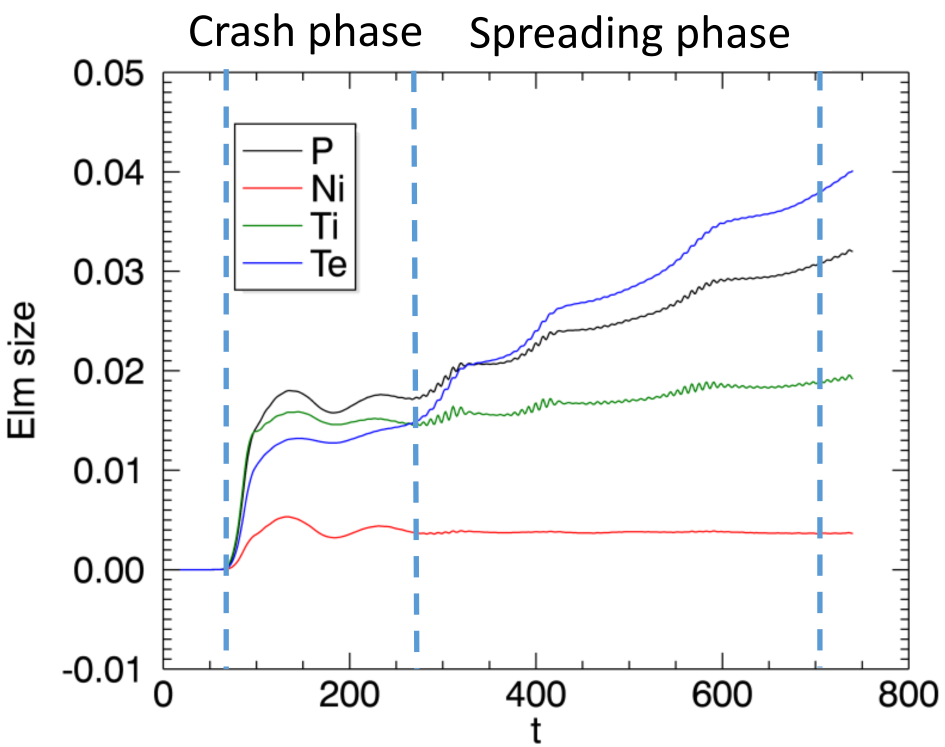
Spreading is strong when L_n/L_t is large

- L_n/L_T has small effect on initial crash phase.
- Speed in spreading phase is large when L_n/L_T is large.
- When L_n/L_T is small, result with Landau closure has more damping effect on ELM size. When L_n/L_T is large, ELM size with Landau closure has faster spreading speed than flux limited case.

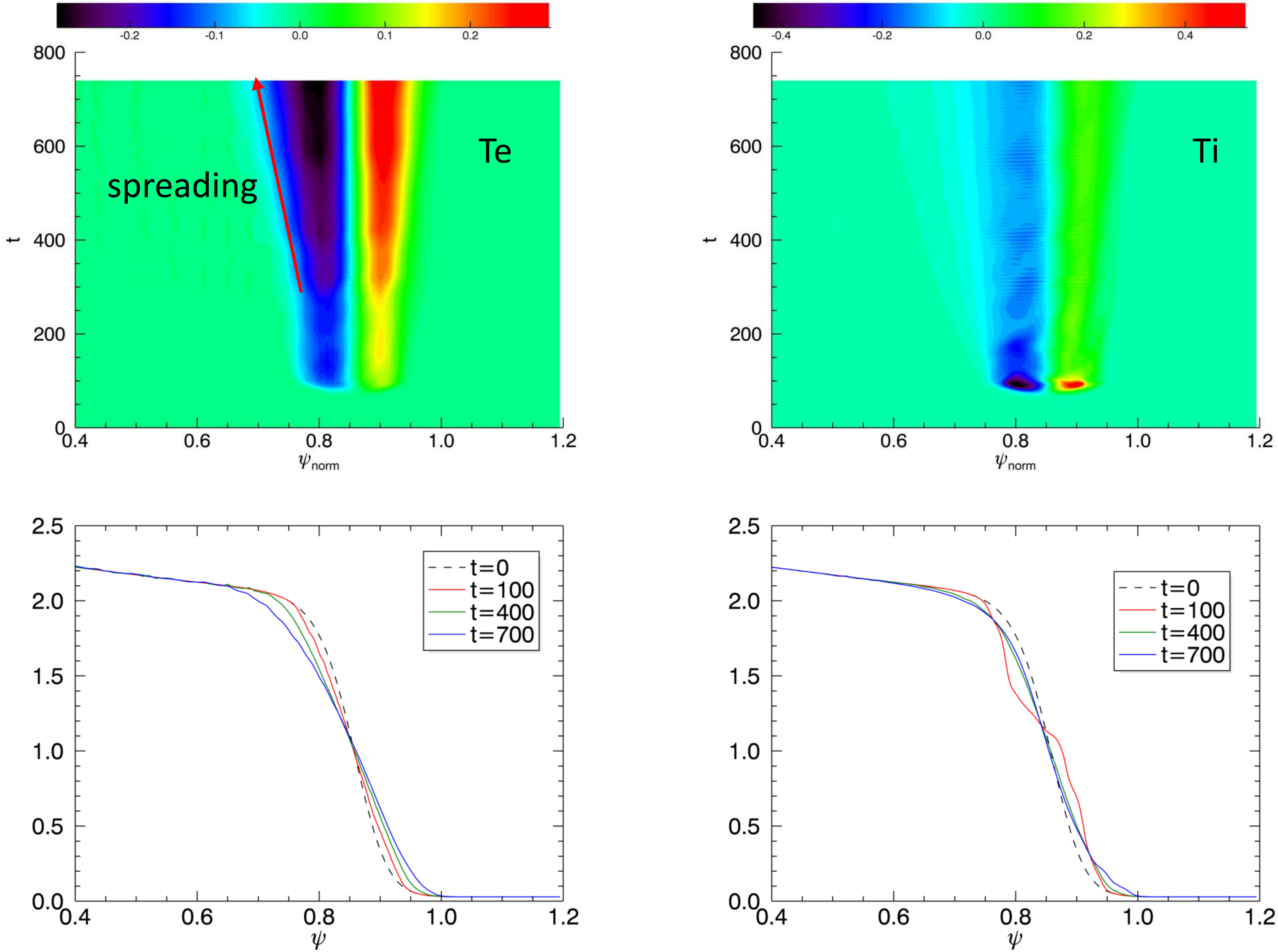


ELM has fast crash phase and slow perturbation spreading phase

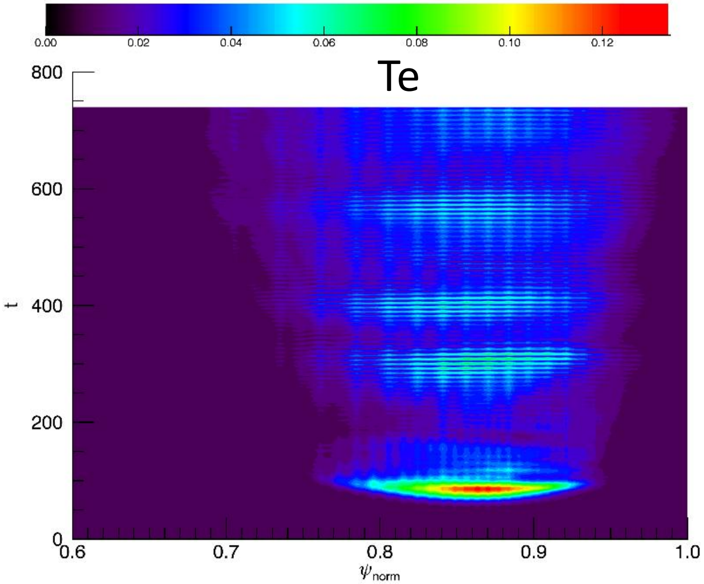
- Ion perturbation has larger initial crash
- Electron provides the spreading

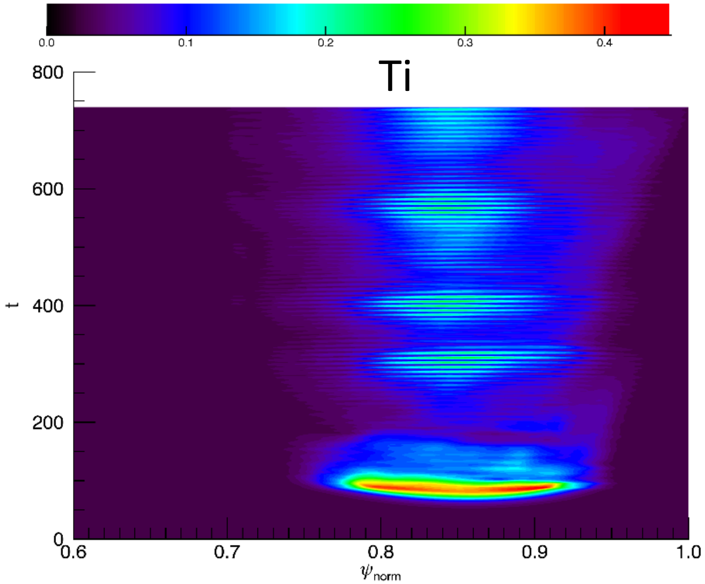


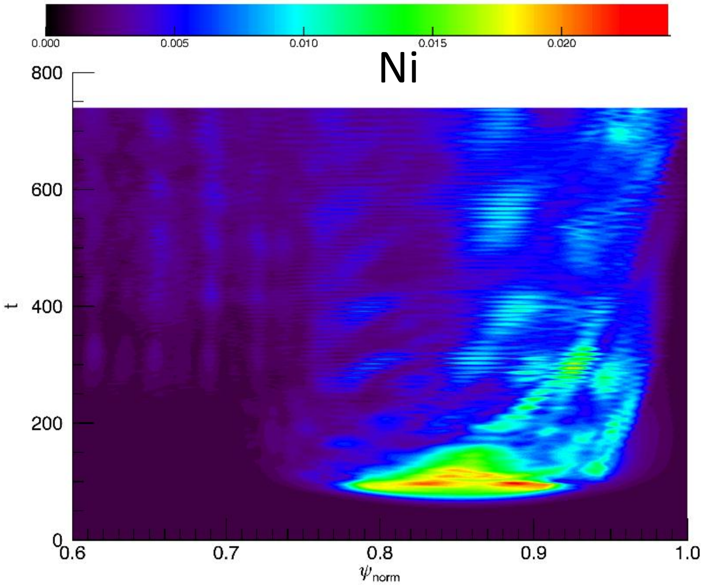
Ion purturbation has a large initial crash and electron purturbation only has spreading

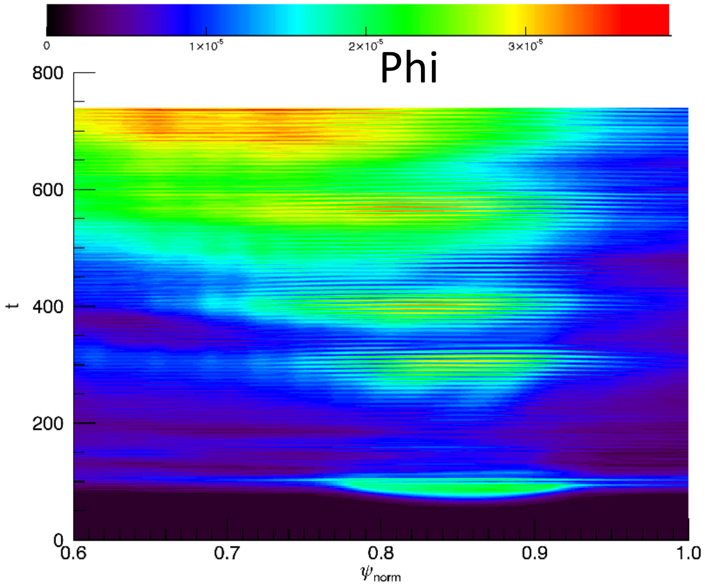


Rms component of perturbation

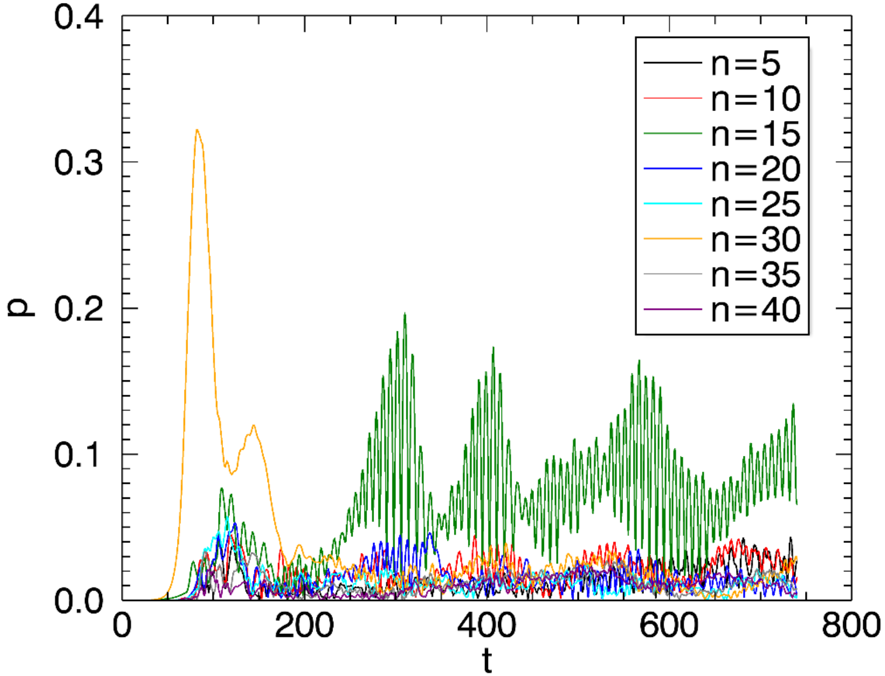


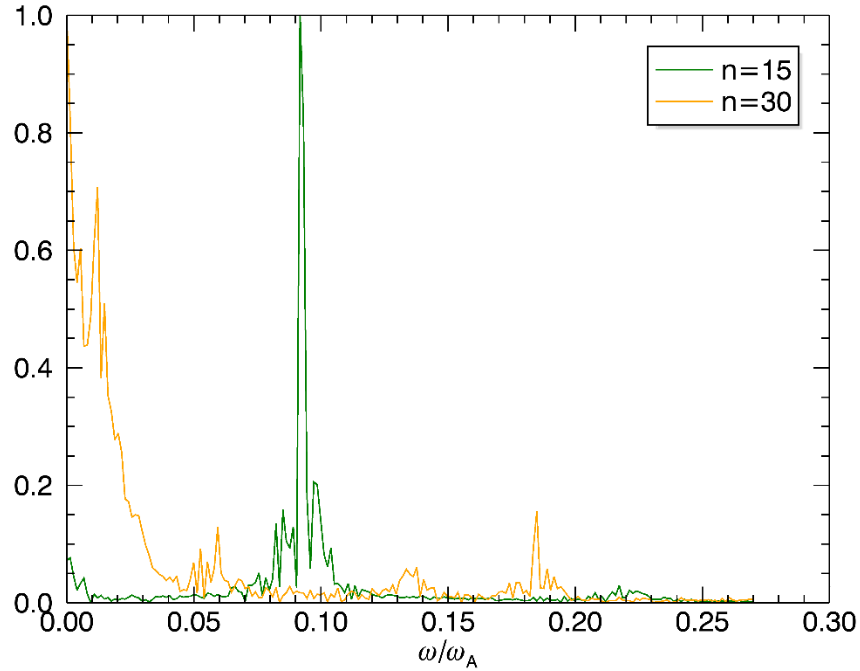




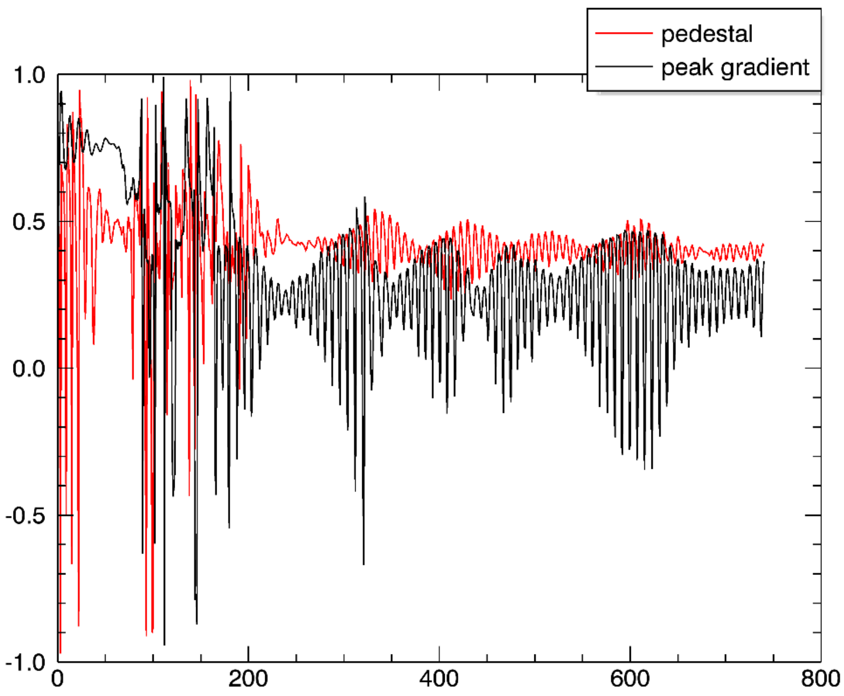


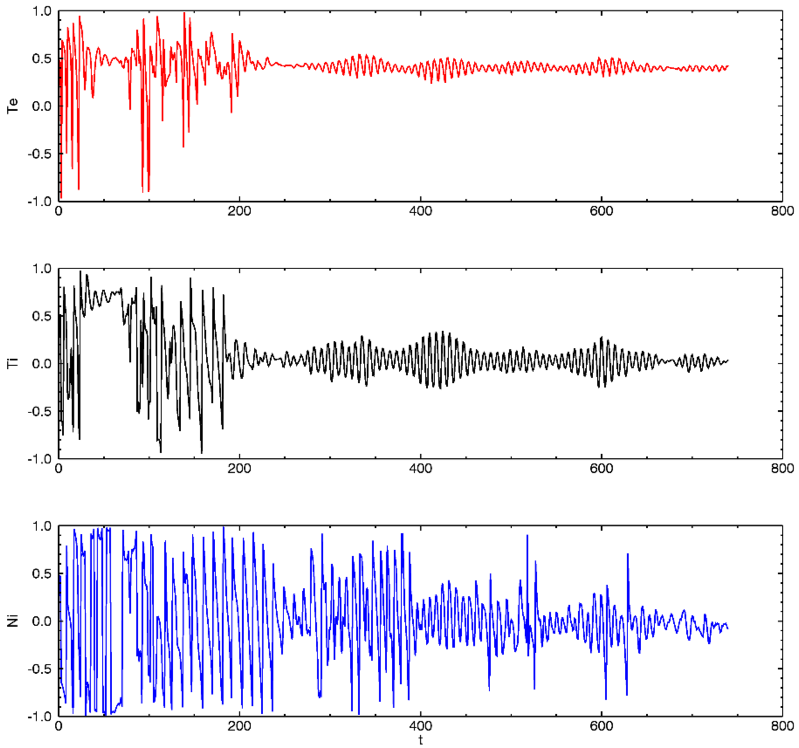
Dominant mode number changed in different phases





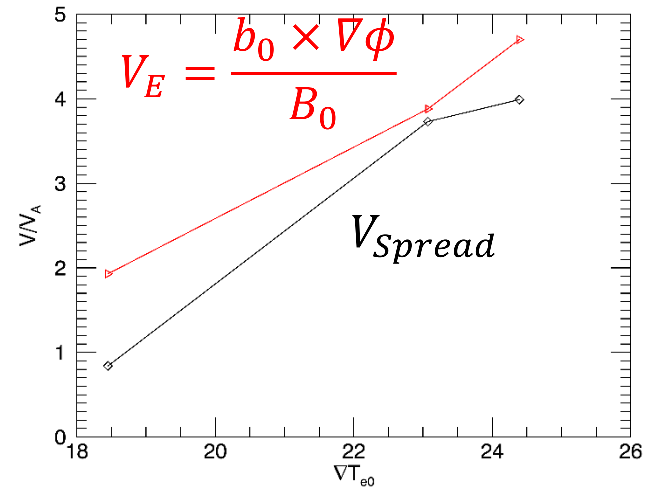
Electron has a positive phase shift with phi

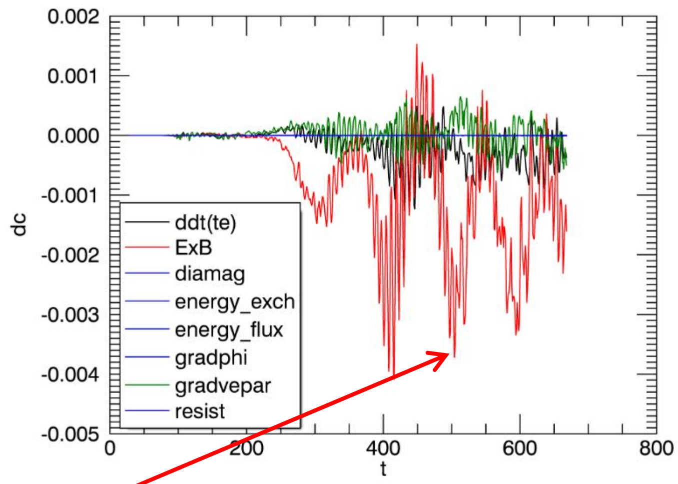




ExB drift term in electron temperature equation cause the spreading

- Drift velocity in electron equation is similar with spreading speed
- Drift wave instability cause the spreading
- Dissipation effect, (Landau damping, parallel thermal conductivity), destabilize the instability.



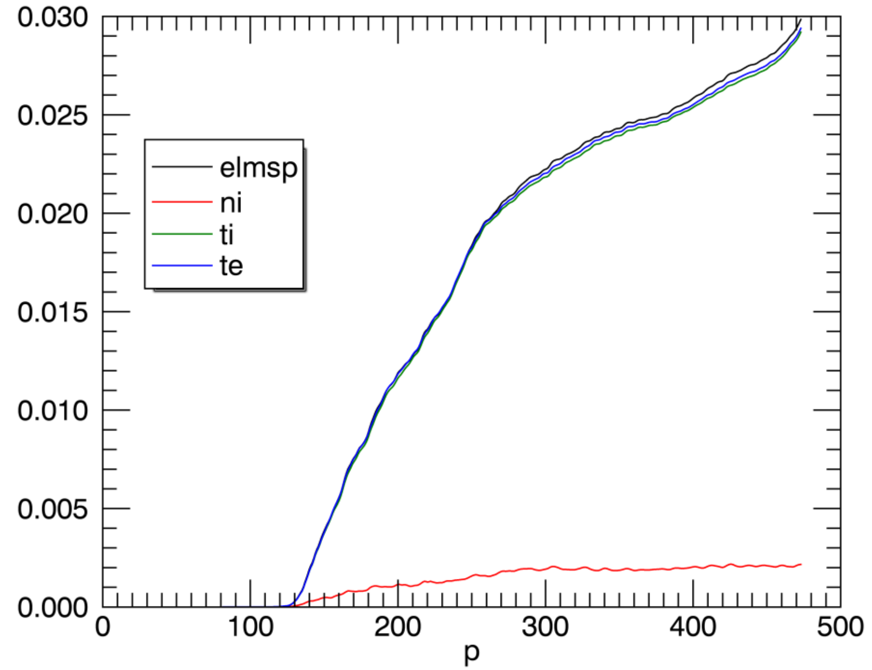


$$\frac{\partial\langle T_e\rangle}{\partial t} = -\frac{1}{B_0}\langle b \times \nabla_\perp \phi \cdot \nabla T_e\rangle$$

Larger conductivity leads to the spreading for electron perturbation

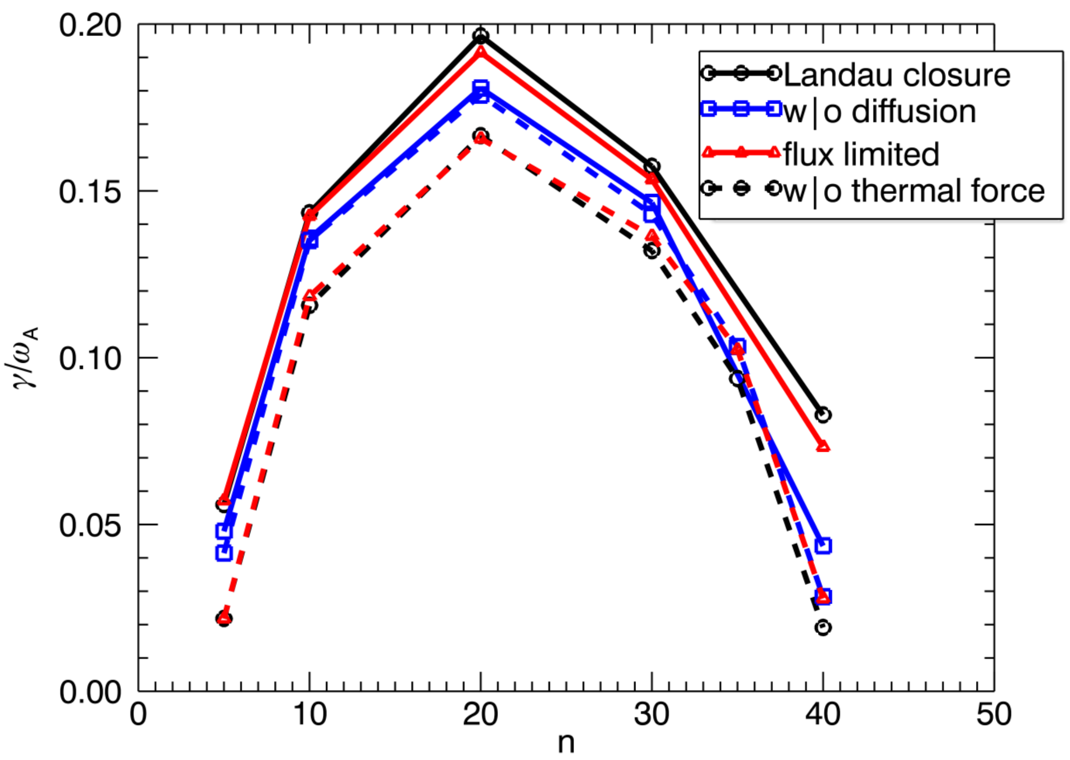
- With larger thermal conductivity, Ion perturbation has same ELM size as electron perturbation.

$$q_i = -\kappa_e \nabla_\parallel T_i$$



Thermal force, when coupled with parallel heat flux, can destabilizes modes

- With Landau closure or flux limited diffusion: Thermal force has an unstable effect on modes;
- Without parallel diffusion: Thermal force has small effect on the linear growth rate of modes.



Summary

- Parallel conductivity term has stabilize effect on peeling-ballooning mode and can reduce elm size.
- Landau closure has more damping effect for the linear growth rate of peeling-ballooning mode.
- Spreading is caused by drift wave instability. Speed for electron perturbation is determined by ExB drift velocity which is large when ∇T_e is large.
- Different response of ion and electron in nonlinear ELM simulation is compared.